

(12)

EUROPEAN PATENT APPLICATION

(21) Application number: 84104038.9

(51) Int. Cl.³: **G 01 N 24/08**

(22) Date of filing: 11.04.84

(30) Priority: 14.04.83 JP 66038/83

(43) Date of publication of application:
24.10.84 Bulletin 84/43

(84) Designated Contracting States:
DE FR GB NL

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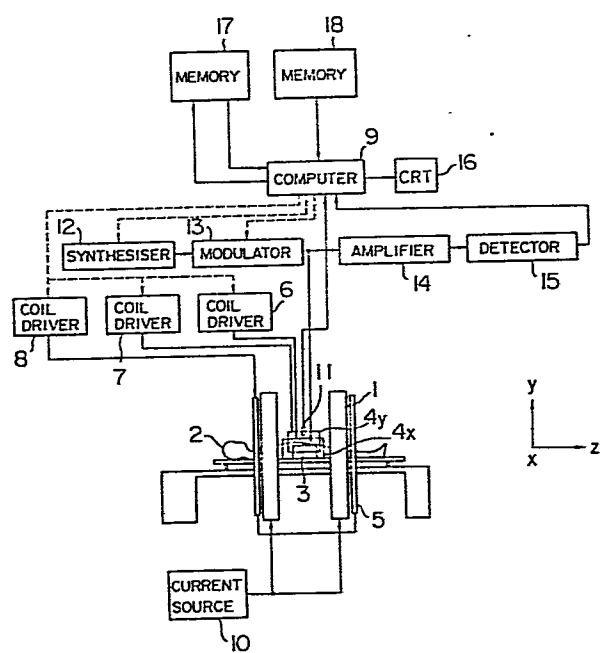
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(54) **Imaging apparatus and method using nuclear magnetic resonance.**

(57) An NMR imaging apparatus and method for direct Fourier imaging. This apparatus includes a static magnetic field generator (1, 10), gradient magnetic field generators (4x, 4z, 5, 6, 7, 8), high-frequency magnetic field generator (3, 12, 13), signal detecting detector (3, 14, 15) for detecting a nuclear magnetic resonance signal from a body (2) to be inspected, a computer (9) for performing an arithmetic operation for the detected signal to obtain the nuclear magnetic resonance intensity distribution in the to-be-inspected body from measured values of the nuclear magnetic resonance intensity distribution at various points on a rectangular coordinate system in the Fourier space, and memories (17, 18) used for correction. In the imaging apparatus, that distortion of image data obtained by calculation from the detected signal which is caused by the deviation of the intensity of the static magnetic field from a predetermined value or the deviation of the intensity of a gradient magnetic field from a predetermined, linearly-varying intensity, is corrected by those measured values with respect to the above deviation of magnetic field intensity which are previously in the memory (18), and corrected image data is displayed on a display device (16).

FIG. 1



IMAGING APPARATUS AND
METHOD USING NUCLEAR MAGNETIC RESONANCE

1 The present invention relates to an imaging
apparatus and a method using the nuclear magnetic resonance
(hereinafter simply referred to as "NMR"), and more
particularly to an NMR imaging apparatus and method which
5 can completely remove the influence of the non-uniformity
of a static magnetic field and the non-linearity of a
gradient magnetic field upon the image quality of an image
formed by NMR imaging.

 In an NMR imaging apparatus (hereinafter simply
10 referred to as an "imaging apparatus"), the density distribu-
tion or relaxation time distribution of nuclear spin in
a body to be inspected, is nondestructively detected by
using the NMR phenomenon, and the cross section of a
measuring target of the to-be-inspected body is reconstruct-
15 ed on the basis of the above distribution.

 The projection-reconstruction method for forming
the image of the cross section has been known. In this
method, the projection of the spin density distribution
or relaxation time distribution in the cross section is
20 formed for various directions, and data thus obtained is
processed to reconstruct the spin density distribution or
relaxation time distribution in the cross section.

 Further, another method for forming the image of
the cross section, that is, the so-called direct Fourier
25 imaging method has been known. In this method, the value

1 of the Fourier transform of the spin density distribution
or relaxation time distribution in the cross section
is directly measured at points on a Cartesian Coordinate
Matrix in the Fourier space. The direct Fourier imaging
5 method includes, for example, the Fourier zeugmatography
proposed by A. Kumar et al. (refer to Journal of Magnetic
Resonance Vol. 13, 1975, pages 69 to 83) and the spin warp
imaging proposed by W.A. Edelstein et al. (refer to Physics
in Medicine & Biology Vol. 25, 1980, pages 751 to 756).

10 An imaging apparatus using the direct Fourier
imaging method is required to have a static magnetic
field having a uniform intensity distribution in a field
of view, and a gradient magnetic field superposed on the
static magnetic field for giving spatial information
15 to a signal. However, in the case where the intensity
distribution of the static magnetic field is non-uniform
or the intensity of the gradient magnetic field varies non-
linearly, there arises a problem that a distortion is produc-
ed on the image of a cross section.

20 Further, the non-uniformity of the static
magnetic field and the non-linearity of the gradient
magnetic field produce an error in the intensity of
an image signal. Accordingly, in the case where the
intensity distribution of the static magnetic field
25 is extremely non-uniform or the intensity change of the
gradient magnetic field is extremely non-linear, undesir-
able errors in the image intensities are produced.

Incidentally, an imaging apparatus capable of

1 removing the influence of the non-uniformity of a static
magnetic field and the non-linearity of a gradient
magnetic field upon an image obtained by the projection-
reconstruction method, is disclosed in a Japanese Patent
5 Application (Application No. 23547/1983) entitled "Imaging
Apparatus using Nuclear Magnetic Resonance" and filed by
the present applicant.

An object of the present invention is to provide
an imaging apparatus and an imaging method using the NMR
10 which can correct the distortion of an image caused by
the non-uniformity of a static magnetic field or the non-
linearity of a gradient magnetic field.

Another object of the present invention is to
provide an imaging apparatus and an imaging method using
15 the NMR which can eliminate the error in the intensity
of image signal caused by the non-uniformity of a static
magnetic field or the non-linearity of a gradient magnetic
field.

In order to attain the above objects, in an NMR
20 imaging apparatus for direct Fourier imaging according to
the present invention, the intensity distribution of a
static magnetic field in a field of view and/or the
intensity distribution of a gradient magnetic field in
the field of view is previously measured, and an image
25 obtained on the basis of the presence of the static and
gradient magnetic fields is corrected at each of picture
elements on the image, using the measured data.

Now, supplementary explanation will be made on

1 the above correction. In order to facilitate the explanation,
the case where a two-dimensional image is formed by
the Fourier zeugmatography and the distortion of the
image caused by the non-uniformity of a static magnetic
5 field is corrected, will be explained below, by way of
example.

Let us denote the distribution to be imaged,
the deviation of the intensity of the static magnetic field
from a standard value, the intensity increment of a
10 gradient magnetic field having an intensity gradient in
an x-direction per unit distance and the intensity increment
of a gradient magnetic field having an intensity gradient
in a y-direction per unit distance, as $C(x, y)$, $E(x, y)$,
 G_x , and G_y , respectively. Then, measured data $S(t_x, t_y)$
15 is given by the following equation:

$$S(t_x, t_y) = \int C(x, y) \exp [-2\pi j \gamma \{ (E(x, y) + (G_x x) t_x + (E(x, y) + G_y y) t_y \}] dx dy \quad \dots \quad (1)$$

where γ indicates a gyromagnetic ratio, t_x a period when
the gradient magnetic field having an intensity gradient
in the x-direction is applied, and t_y a period when the
gradient magnetic field having an intensity gradient in
20 the y-direction is applied. It should be noted that
 T_1 and T_2 relaxations are neglected in the equation (1).

Now, let us use the following integral variables:

$$\left. \begin{aligned} x' &= x + \frac{1}{G_x} E(x, y) \\ y' &= y + \frac{1}{G_y} E(x, y) \end{aligned} \right\} \dots\dots (2)$$

1 Then, the equation (1) can be changed to the following equation:

$$S(t_x, t_y) = \int C'(x', y') \exp[-2\pi j (G_x x' t_x + G_y y' t_y)] dx' dy' \dots\dots (3)$$

where

$$C'(x', y') = \frac{C(f_1(x', y'), f_2(x', y'))}{1 + \frac{1}{G_y} \frac{\partial E(x, y)}{\partial y} + \frac{1}{G_x} \frac{\partial E(x, y)}{\partial x}} \dots (4)$$

In the equation (4), $f_1(x', y')$ and $f_2(x', y')$
 5 indicate $X = f_1(x', y')$ and $Y = f_2(x', y')$ which are obtained by solving the equations (2).

In general, the above-mentioned gradient magnetic fields are applied so as to satisfy the following formulae:

$$G_y \gg \frac{\partial E(x, y)}{\partial y}, \text{ and } G_x \gg \frac{\partial E(x, y)}{\partial x} \dots\dots (5)$$

10 Accordingly, the equation (4) can be rewritten as follows:

$$C'(x', y') \doteq C(f_1(x', y'), f_2(x', y')) \dots\dots (6)$$

When two-dimensional inverse Fourier transformation is carried out for the measured data $S(t_x, t_y)$,

1 the distribution $C'(x', y')$ is obtained as is shown in
eq. (3). It is clear from the formula (6) that the
distribution $C'(x', y')$ is considered to be obtained by
carrying out the transformation of coordinate system
5 for the original distribution $C(x, y)$ on the basis of
the equations (2). In other words, owing to the non-
uniformity of the static magnetic field in a field of view,
the image of a cross section is subjected to a distortion
which is indicated by the equation (2).

10 In an ordinary imaging apparatus, a gradient
magnetic field having an intensity gradient of 0.2 to 0.3
gauss/cm is used. Further, even a static magnetic field
formed by the best one of magnets which are available at
the present, has an intensity variation of about 3×10^{-3}
15 percent in field of view having a diameter of 40 cm. In
such a case, each of a difference $x-x'$ and a difference
 $y-y'$ approximately corresponds to one picture element and
a half. Accordingly, a distortion on the order of two
picture elements will be produced on the image of a cross
20 section.

As mentioned previously, according to the present
invention, the deviation $E(x, y)$ of the intensity of a
static magnetic field from a standard value is previously
measured, and the measured data thus obtained is used for
25 correcting the image $C'(x', y')$ which is affected by the
non-linearity of the static magnetic field, on the basis
of the relations between coordinates (x, y) and coordinates
 (x', y') given by the equations (2).

1 Further, in the case where the intensity change
of a gradient magnetic field deviates from a predetermined
straight line to some extent, the deviation of the
intensity of the gradient magnetic field from a linearly-
5 varying intensity is previously measured together with
the above-mentioned deviation $E(x, y)$ with respect to the
static magnetic field, and the measured data thus obtained
is used for correcting the image $C'(x', y')$ which is
affected by the non-uniformity of the static magnetic
10 field and the non-linearity of the gradient magnetic field.

Other features of the present invention will
become apparent from the following detailed description
taken in conjunction with the accompanying drawings, in
which:

15 Fig. 1 is a block diagram showing an embodiment
of an NMR imaging apparatus according to the present
invention; and

Figs. 2 to 5 are waveform charts showing dif-
ferent pulse sequences applicable to the embodiment
20 shown in Fig. 1.

Now, the present invention will be explained
below in detail, with reference to the drawings. Fig. 1
show the outline of an embodiment of an NMR imaging
apparatus according to the present invention. In Fig. 1,
25 reference numeral 1 designates a magnet for generating
a static magnetic field H_0 , 2 a body to be inspected,
3 a detecting coil for generating a high-frequency magnetic
field and for detecting a signal produced by the to-be-

1 inspected body 2, 4x coil means for generating a gradient
magnetic field having an intensity gradient in the x-
direction (hereinafter referred to as an "x-gradient
magnetic field"), 4y coil means for generating a gradient
5 magnetic field having an intensity gradient in the y-
direction (hereinafter referred to as a "y-gradient magnetic
field"), and 5 coil means for generating a gradient magnetic
field having an intensity gradient in the z-direction
(hereinafter referred to as a "z-gradient magnetic field").
10 Coil drivers 6, 7, and 8 supply currents to the coil means
4x, 4y, and 5, respectively, and each of the coil drivers
6, 7, and 8 is operated by a signal from a computer 9.
The coil means 5 is formed of a pair of one-turn coils
which are connected so as to be opposite in current direc-
15 tion to each other. The intensity of a gradient magnetic
field generated by the coil means 4x, 4y, and 5 can be
varied by an instruction from a device 11 for detecting
the size of the to-be-inspected body 2 or from the operator
of the imaging apparatus. Incidentally, reference numeral
20 10 designates a current source for supplying an exciting
current to the magnet 1.

A high-frequency magnetic field for exciting a
nuclear spin is generated in such a manner that a high-
frequency signal generated by a synthesizer 12 is shaped
25 and power-amplified by a modulator 13 and a high-frequency
current is supplied from the modulator 13 to the coil 3.
A signal from the to-be-inspected body 2 is received by
the coil 3, and sent through an amplifier 14 to a detector

1 15, to be subjected to AC-DC conversion. The signal thus
treated is applied to the computer 9. Image data $C'(I', J')$
is calculated from the signal supplied to the computer 9,
and stored in a memory 17. Since the image data stored in
5 the memory 17 has a distortion, the image data $C'(I', J')$
is corrected by data which is previously stored in a
memory 18. Corrected image data $C(I, J)$ is displayed on
a CRT display 16.

First, detailed explanation will be made on
10 an example of the correction according to the present
invention, that is, the case where the image of a cross
section is formed by the two-dimensional Fourier zeugmato-
graphy, and the distortion of the image caused by the non-
uniformity of a static magnetic field is corrected.

15 Fig. 2 shows a time when each of a high-
frequency pulse (namely, an RF pulse), an x-gradient magnetic
field, and a y-gradient magnetic is applied to carry out
the two-dimensional Fourier zuegmatography, and a time
when a signal from a nuclear spin is detected. The pulse
20 sequence shown in Fig. 2 is used for forming the image
of a desired cross section parallel to the x-y plane. In
Fig. 2, reference symbol RF designates an RF pulse, G_y a
y-gradient magnetic field having an intensity gradient G_y ,
 G_x an x-gradient magnetic field having an intensity gradient
25 G_x , and NS a signal from a nuclear spin. As is apparent
from Fig. 2, a 90° RF pulse is first applied to a to-be-
inspected body, to tilt the nuclear spin in the body by
an angle of 90° . Immediately thereafter, the Y-gradient

1 magnetic field is applied for a period t_y . As soon as
the period t_y terminates, the X-gradient magnetic field
is applied and the observation of NMR signal is started.
Using the pulse sequence shown in Fig. 2, the object spin-
5 density is measured on the rectangular coordinate points
in the Fourier space. The above measurement is carried
out for various values of the period t_y . A two-dimensional
signal $S(t_x, t_y)$ obtained from such measurement for various
values of the period t_y is related to the nuclear spin
10 distribution in the desired cross section, as mentioned
below:

$$S(t_x, t_y) = \int C(x, y) \exp\{-2\pi j \gamma (G_x x t_x + G_y y t_y)\} dx dy$$

..... (7)

However, it is to be noted that the equation (7) holds
only when the intensity distribution of the static magnetic
field is uniform and the intensity of each of the gradient
15 magnetic fields varies linearly in the x- or y-direction,
and that a relaxation term is neglected in the equation (7).
As can be seen from the equation (7), the nuclear spin
distribution (x, y) in the desired cross section can be
obtained by carrying out the two-dimensional inverse
20 Fourier transformation for the two-dimensional signal
 $S(t_x, t_y)$.

The above-mentioned explanation has been made
to show the principle of the Fourier zeugmatography.

In the present example, the two-dimensional

1 inverse Fourier transformation is carried out for a
measured signal $S(t_x, t_y)$ in accordance with the above
principle, and image data thus obtained is stored in the
memory 17. However, the data stored in the memory 17 is
5 not discrete values of $C(I, J)$ (where $I = 0, 1, \dots, N-1$;
 $J = 0, 1, \dots, N-1$) indicating an actual nuclear spin
density distribution $C(x, y)$, but discrete values of
 $C'(I', J')$ (where $I' = 0, 1, \dots, N-1$; $J' = 0, 1, \dots, N-1$)
indicating the image $C'(x', y')$ which has a distortion
10 due to the non-uniformity of the static magnetic field.
For this reason an arithmetic operation for correction
is performed for the values $C'(I', J')$, using data with
respect to the intensity distribution of the static magnetic
field which is previously stored in the memory 18. Thus,
15 data $C(I, J)$ indicating the actual spin density distribu-
tion is obtained. The arithmetic operation for correction
will be explained below in detail. As is evident from
the equations (2), in the case where the intensity of the
static magnetic field at a position corresponding to
20 a picture element in the J -th row, the I -th column deviates
from a standard value by an amount $E(I, J)$, the actual
spin density $C(I, J)$ at this position is equal to the
signal intensity $C'(\xi, \eta)$ at a point having coordinates ξ
and η on the image obtained by the inverse Fourier
25 transformation. The coordinates ξ and η are given by the
following equations:

$$\left. \begin{aligned} \xi &= I + \frac{1}{G_x} E(I, J) \\ \eta &= J + \frac{1}{G_y} E(I, J) \end{aligned} \right\} \dots\dots (8)$$

1 It should be noted that in equation (8), G_x indicates the intensity increment of the X-gradient magnetic field per one picture element, and G_y the intensity increment of the y-gradient magnetic field per one picture element.

5 The point having the coordinates ξ and η does not always coincide with a picture element in the J' -th row, the I' -th column (where $I' = 0, 1, \dots, \text{or } N-1$; $J = 0, 1, \dots, \text{or } N-1$).

10 In the present example, the deviation $E(I, J)$ of the intensity of the static magnetic field from a standard value is measured at each of the positions corresponding to the picture elements, and the coordinates ξ and η are determined by the equations (8). Then, numeral values i, j, Δ_1 , and Δ_2 are determined as follows:

$$\begin{aligned} i &= [\xi], j = [\eta], \Delta_1 = \xi - i, \text{ and } \Delta_2 = \eta - j \\ &\dots\dots (9) \end{aligned}$$

15 These values thus determined are previously stored in the memory 18. Incidentally, the sign $[]$ indicates the greatest integers which do not exceed a value written in the sign $[]$.

20 Then, for each of the positions, the following equation is calculated by the computer 9:

$$g = (1 - \Delta_1)(1 - \Delta_2)C'(i, j) + (1 - \Delta_1)\Delta_2C'(i, j + 1) \\ + \Delta_1(1 - \Delta_2)C'(i + 1, j) + \Delta_1\Delta_2C'(i + 1, j + 1) \dots (10)$$

1 The value g thus obtained is displayed as the
nuclear spin density $C(I, J)$ at the position corresponding
to the picture element in the J -th row, the I -th column.
That is,

$$C(I, J) = g \dots \dots \dots (11)$$

5 In other words, the spin density $C(I, J)$ is
determined, by interpolation, from data at four points
existing around the point (ξ, η) .

 In more detail, the values i , j , Δ_1 , and Δ_2 with
respect to the position corresponding to the picture
10 element in the J -th row, the I -th column are fetched
from the memory 18 into the computer 9, to calculate
values $(i + 1)$, $(j + 1)$, $(1 - \Delta_1)$, and $(1 - \Delta_2)$. Then,
data $C'(i, j)$, $C'(i + 1, j)$, $C'(i, j + 1)$, and $C'(i + 1, j + 1)$
are fetched from the memory 17, to calculate the equa-
15 tion (10). The result of the calculation is used as
corrected image data for the picture element in the J -th
row, the I -th column. The above processing is performed
for all of the picture elements, and the results of such
processing are displayed on the CRT display 16. In the
20 image $C(I, j)$ thus obtained, the distortion due to the
non-uniformity of the static magnetic field will be removed,
if an error caused by interpolation can be neglected.

 In the above example, the values i , j , Δ_1 and Δ_2

1 stored in the memory 18 can be previously calculated by
 an external, large-sized computer. However, in the case
 where the computer 9 has sufficient processing capability.
 the above calculation can be performed by the computer 9.
 5 In this case, the data $E(I, J)$ (where $I = 0, 1, \dots, N-1$;
 $J = 0, 1, \dots, N-1$) with respect to the static magnetic
 field is stored in the memory 18. In order to determine
 the spin density $C(I, J)$, the data $E(I, J)$ at the position
 corresponding to the picture element in the J -th row, the
 10 I -th column is first fetched from the memory 18, and the
 coordinates ξ and η are calculated from the equations (8).
 Then, the values i , j , Δ_1 , and Δ_2 are determined from
 the equations (9).

Next, explanation will be made on another
 15 example of the correction according to the present inven-
 tion, that is, the case where the distortion of an image
 caused by both the non-uniformity of a static magnetic
 field and the non-linearity of gradient magnetic fields
 is corrected. This correction also can be carried out by
 20 the embodiment shown in Fig. 1.

First, the principle of correction in the present
 example will be explained. In the case where the intensity
 of a gradient magnetic field varies non-linearly, the
 intensity of the x -gradient magnetic field and that of the
 25 y -gradient magnetic field can be expressed by

$$G_x\{x+h_1(x, y)\} \text{ and } G_y\{y+h_2(x, y)\} \dots\dots (12)$$

1 where $h_1(x, y)$ indicates the deviation of the intensity
of the x-gradient magnetic field from a linearly-varying
intensity, and $h_2(x, y)$ the deviation of the intensity
of the y-gradient magnetic field from a linearly-varying
5 intensity. In the present example, the two-dimensional
signal $S(t_x, t_y)$ is given by the following equation:

$$S(t_x, t_y) = \int C(x, y) \exp[-2\pi j \gamma \{ (E(x, y) + G_x(x + h_1(x, y)) \\ + (E(x, y) + G_y(y + h_2(x, y))) t_y \}] dx dy \dots (13)$$

The above equation (13) can be converted into
the equation (3) by using integral variables x' and y'
which are given by the following equations:

$$\left. \begin{aligned} x' &= x + \frac{1}{G_x} E(x, y) + h_1(x, y) \\ y' &= y + \frac{1}{G_y} E(x, y) + h_2(x, y) \end{aligned} \right\} \dots (14)$$

10 Accordingly, in the present example, the following
equations (18) are used in place of the equations (8):

$$\left. \begin{aligned} \xi' &= I + \frac{1}{G_x} E(I, J) + h_1(I, J) \\ \eta' &= J + \frac{1}{G_y} E(I, J) + h_2(I, J) \end{aligned} \right\} \dots (15)$$

That is, the deviation $E(I, J)$ with respect to the static
magnetic field and the deviation $h_1(I, J)$ and $h_2(I, J)$
with respect to the gradient magnetic fields should be
15 measured at each of positions corresponding to picture

1 elements. Note that in equation (15), G_x and G_y are the
increments per one picture element. The coordinates ξ'
and η' are calculated from the equations (15), using the
measured values of $E(I, J)$, $h_1(I, J)$, and $h_2(I, J)$. Then,
5 values $\underline{i}$, $\underline{j}$, Δ_1 , and Δ_2 for each position are determined
as follows:

$$\left. \begin{aligned} i &= [\xi'], j = [\eta'] \\ \Delta_1 &= \xi' - i, \Delta_2 = \eta' - j \end{aligned} \right\} \dots\dots (16)$$

These data $\underline{i}$, $\underline{j}$, Δ_1 , and Δ_2 are previously stored
in the memory 18. Then, the spin density $C(I, J)$ at each
position is calculated from the equation (10) (that is,
10 by interpolation), using uncorrected image data $C(i, j)$,
 $C(i, j+1)$, $C(i+1, j)$, and $C(i+1, j+1)$ stored in the
memory 17 and data $\underline{i}$, $\underline{j}$, Δ_1 , and Δ_2 stored in the memory
18. When the spin density $C(I, J)$ thus obtained is
displayed on the CRT display 16, an image can be obtained
15 in which the distortion due to both the non-uniformity of
the static magnetic field and the non-linearity of the
gradient magnetic fields has been corrected.

In the present example, the data $\underline{i}$, $\underline{j}$, Δ_1 , and Δ_2
are stored in the memory 18. However, the data $E(I, J)$
20 with respect to the static magnetic field and the data
 $h_1(I, J)$ and $h_2(I, J)$ with respect to the gradient magnetic
fields may be stored, instead of the data $\underline{i}$, $\underline{j}$, Δ_1 , and Δ_2 .
In such a modified version of the present example, the
computer 9 is required to perform arithmetic operations

1 given by the equations (15) and (16), prior to the
calculation for interpolation.

In the above description, the present invention
has been explained for the case where the two-dimensional
5 Fourier zeugmatography is used. However, the present
invention is not limited to the two-dimensional Fourier
zeugmatography, but is applicable to the spin warp imaging
in a manner as mentioned below. (As mentioned previously,
the spin warp imaging is another one of the direct Fourier
10 imaging methods in which the values of the nuclear spin
density distribution in a to-be-inspected body are measured
at points on a rectangular coordinate system in the Fourier
space.)

Fig. 3 shows an operation for deriving the image
15 of a cross section by the two-dimensional spin warp imaging,
and corresponds to Fig. 2 which shows an operation accord-
ing to two-dimensional Fourier zeugmatography. In Fig. 3,
the same reference symbols as in Fig. 2 are used in the
same sense as in Fig. 2.

20 The spin warp imaging shown in Fig. 3 is dif-
ferent in the operation at a second period (2) from the
Fourier zeugmatography shown in Fig. 2. That is, in the
Fourier zeugmatography, the period t_y when the y-gradient
magnetic field is applied, is set to have various values in
25 the second period (2), and measurement the NMR signal is
measured for each value of the period t_y . While, in the
spin warp imaging, the period t_y is fixed (that is, the
y-gradient magnetic field is applied for a fixed period t_0),

- 1 but the amplitude of gradient G_y is set to have various
values. That is, the measurement of NMR signal is performed
for each value of G_y . A two-dimensional signal $S(G_y, t_x)$
thus obtained is related to the actual spin density
5 distribution $C(x, y)$, as mentioned below:

$$S(G_y, t_x) = \int C(x, y) \exp[-2\pi j \gamma \{ (E(x, y) + G_x(x + h_1(x, y))t_x \\ + E(x, y)t_c + G_y(y + h_2(x, y))t_0 \}] dx dy \dots (17)$$

- It is to be noted that a relaxation term is neglected in
the equation (17) and the intensity of the y-gradient
magnetic field is expressed by $G_y(y + h_2(x, y))$.
Incidentally, reference symbol t_c in Fig. 3 indicates a
10 time interval between a time when a 90° RF pulse is
applied and a time when the observation of spin echo is
started. The equation (17) can be changed to the follow-
ing equation:

$$S(G_y, t_x) = \int C(x, y) e^{-2\pi j \gamma E(x, y) t_c} \\ \exp[-2\pi j \gamma \{ E(x, y) + G_x h_1(x, y) \\ + G_x x) t_x + G_y t_0 (y + h_0(x, y)) \}] dx dy \dots (18)$$

- Now, let us perform the following transformation
15 of coordinate system:

$$\left. \begin{aligned} x' &= x + \frac{1}{G_x} E(x, y) + h_1(x, y) \\ y' &= y + h_2(x, y) \end{aligned} \right\} \dots (19)$$

1 Then, the equation (19) is changed to the following equation:

$$S(G_y, t_x) = \int C'(x', y') \exp[-2\pi j \gamma (G_x x' t_x + G_y y' t_0)] dx dy \quad \dots\dots (20)$$

From the equations (19), the coordinates x and y can be expressed as follows:

$$\left. \begin{aligned} x &= g_1(x', y') \\ y &= g_2(x', y') \end{aligned} \right\} \quad \dots\dots (21)$$

5 By using the equations (21), the image data $C'(X', Y')$ is given by the following equation:

$$C'(x', y') = C'(g_1(x', y'), g_2(x', y')) e^{-2\pi j \gamma E(g_1(x', y'), g_2(x', y')) t_c} \quad \dots\dots (22)$$

Thus, the absolute value of the image data is given as follows:

$$|C'(x', y')| = |C(g_1(x', y'), g_2(x', y'))| \quad \dots\dots (23)$$

The equation (23) shows that the absolute value of the
10 image data is distorted by the non-uniform intensity distribution of a static magnetic field and the non-linear intensity distribution of gradient magnetic fields. Such a distortion can be corrected in the same manner as in

1 the previously-mentioned Fourier zeugmatography, except
that the following equations (24) are used in place of the
equations (8).

$$\left. \begin{aligned} \xi &= I + \frac{1}{G_x} E(I, J) + h_1(I, J) \\ \eta &= J + h_2(I, J) \end{aligned} \right\} \dots (24)$$

where G_x indicates the intensity increment of the x-gradient
5 magnetic field per one picture element, as in the equations
(8) and (15).

The above-mentioned processing for the correc-
tion is performed by the embodiment shown in Fig. 1, in
accordance with the following procedure. The error $E(I, J)$
10 in a static magnetic field and errors $h_1(I, J)$ and $h_2(I, J)$
in gradient magnetic fields are measured at each of the
positions corresponding to picture elements, and then
the coordinates ξ and η are calculated from the equations
(24). The values (i, j) and (Δ_1, Δ_2) are determined by
15 the equations (9), and stored in the memory 18. The computer
9 performs the arithmetic operation for interpolation
given by the equation (10), for each of the positions
corresponding to the picture elements, using the data
stored in the memory 18 and uncorrected image data $C'(I', J')$
20 stored in the memory 17. The results of the above
arithmetic operation are displayed, as the image data
 $C(I, J)$, on the CRT display 16.

Further, in this case, measured data $E(I, J)$,

1 $h_1(I, J)$, and $h_2(I, J)$ indicating errors in the magnetic
fields may be stored in the memory 18, provided that the
computer 9 performs the arithmetic operations given by
the equations (24) and (9), prior to the arithmetic
5 operation for interpolation.

As can be seen from the equations (19) and (20),
according to the spin warp imaging, the non-uniformity of
the static magnetic field causes a distortion only in the
x-direction of the image, and does not cause any distort-
10 tion in the y-direction, if the deviation of the intensity
distribution of each gradient magnetic field from a
linear intensity distribution is negligibly small. In
this case, only the values ξ , i , and Δ_1 are determined
by the following equations:

$$\xi = I + \frac{1}{G_x} E(I, J) \dots\dots\dots (25)$$

$$i = [\xi] \dots\dots\dots (26)$$

$$\Delta_1 = \xi - i \dots\dots\dots (27)$$

15 Further, in order to correct the distortion of the image,
the computer 9 performs the following arithmetic operation
for interpolation between two points:

$$C(I, J) = (1 - \Delta_1) C'(i, J) + \Delta_1 C'(i + 1, J) \dots\dots (28)$$

In the foregoing description, explanation has
been made using the original sequences which have

1 been devised by the proposers of each of the Fourier
zeugmatography and the spin warp imaging. However,
in addition to the original sequences, various modified
sequences are now used which are improved versions of the
5 original sequences. Now, the present invention will be
explained for the case where the improved sequences are
used.

Figs. 4 and 5 show examples of the improved
sequences. The main feature of the sequences shown in
10 Figs. 4 and 5 resides in that a spin echo is formed by
using a 180° pulse.

The operation at each of first, second, third,
and fourth periods (1), (2), (3), and (4) shown in Fig. 4
will be explained below, by way of example.

15 At the first period (1), a 90° RF pulse accord-
ing to the selective irradiation method is emitted while
applying the z-gradient magnetic field to the to-be-inspected
body, so that the nuclear spin in a specified cross
section parallel to the x-y plane is inclined by an angle
20 of 90° . For details of the RF pulse according to the
selective irradiation method, an article entitled "Medical
Imaging by NMR" (British J. of Radiography, Vol. 50, 1977,
pages 188 to 194) should be referred to.

At the second period (2), a 180° RF pulse
25 according to the selective irradiation method is emitted
when a time τ has elapsed after the 90° RF pulse was
emitted, and thus the nuclear spin in the cross section
which is selected at the first period (1), is reversed in

1 orientation, to observe an echo signal when a time 2τ has
elapsed after the 90° RF pulse was emitted.

At the third period (3), the y-gradient magnetic
field is applied for a time t_y .

5 At the fourth period (4), the x-gradient magnetic
field is applied and the measurement of the echo signal
is started, immediately after the y-gradient magnetic
field is removed.

The time t_y (that is, a period when the y-gradient
10 magnetic field is applied) is set to various values, and
the above measurement is made for each of such values.
A two-dimensional signal $S(t_x, t_y)$ thus obtained is given
as follows:

$$S(t_x, t_y) = \int C(x, y) \exp[2\pi j \gamma \{G_y y t_y + (E(x, y) + G_x x) t_x\}] dx dy$$

.... (29)

In deriving equation (29), it is assumed that field
15 gradient non-linearities are negligible. It is to be
noted that the non-uniformity of the static magnetic
field has no effect on the image in the y-direction, as
in the spin warp imaging shown in Fig. 3. This is
because an echo is formed by using the 180° RF pulse.

20 The sequence shown in Fig. 5 is different from
that shown in Fig. 4 in that the y-gradient magnetic
field is applied for a fixed time t_0 , and the amplitude
thereof is set to various values. Accordingly, in this

1 case, a two-dimensional signal $S(t_x, G_y)$ is given as follows:

$$S(t_x, G_y) = \int C(x, y) \exp[-2\pi j \gamma \{G_y y t_0 + (E(x, y) + G_x x) t_x\}] dx dy$$

.... (30)

Thus, the non-uniformity of the static magnetic field produces no effect on the image in the y-direction. Accordingly, in the case where either one of the sequences shown in Figs. 4 and 5 is used, the distortion of the image can be corrected in the same manner as the absolute value of the image data which is obtained by using the sequence shown in Fig. 3, is corrected. That is, in the case where it is required to correct the distortion caused only by the non-uniformity of the static magnetic field, the coordinate ξ is calculated from the equation (25), and correction is made by the equation (28). Further, in the case where it is required to correct the distortion caused by both the non-uniformity of the static magnetic field and the non-linearity of the gradient magnetic fields, the coordinates ξ and η are calculated from the equations (24), and correction is made by the equation (10).

In various examples mentioned above, the deviation $E(I, J)$ of the intensity of the static magnetic field from a standard value and the deviation $h_1(I, J)$ and $h_2(I, J)$ of respective intensities of the gradient magnetic fields from linearly-varying intensities are

1 measured at each of the positions corresponding to picture
elements, and data necessary for correcting the distortion
of the image are calculated from the measured values,
to be stored in the memory 18. However, it takes a lot of
5 time to obtain the measured values. Accordingly, the
deviation with respect the static magnetic field and
the deviation with respect to the gradient magnetic field
may be measured at intervals of several positions, to
determine deviation values at the positions where measure-
10 ment is not made, by interpolation. Further, in the case
where the intensity distribution of the static magnetic
field and that of each gradient magnetic field can be
approximated with some functions, the values of the deviation $E(I, J)$, $h_1(I, J)$, and $h_2(I, J)$ used in the above-
15 mentioned examples may be calculated from such functions.

In the foregoing description, various examples
of the correction according to the present invention
have been explained on the assumption that the formulae
(5) hold. However, in the case where the intensity
20 distribution of the static magnetic field is extremely
non-uniform, the formulae (5) do not hold, and therefore
the denominator on the right-hand side of the equation (4)
has to be corrected.

Now, the processing in such a case will be
25 explained below.

When the denominator on the right-hand side of
the equation (4) is expressed by W , the denominator W is
given as follows:

$$W = 1 + \frac{1}{G_y} \frac{\partial E(x, y)}{\partial y} + \frac{1}{G_x} \frac{\partial E(x, y)}{\partial x} \dots\dots (31)$$

1 By using discrete variables I and J in place of the continuous variables x and y, the equation (31) is changed to the following equation:

$$W = 1 + \frac{1}{G_y} \{E(I, J+1) - E(I, J)\} + \frac{1}{G_x} \{E(I+1, J) - E(I, J)\} \dots\dots (32)$$

where G_x indicates the field gradient increment per one
5 picture element in the x-direction, and G_y the field gradient increment per one picture element in the y-direction. As mentioned previously, the value of $E(I, J)$ can be determined by measurement.

In order to obtain corrected image data $C(I, J)$
10 for a picture element in the J-th row, the I-th column, the values i, j, Δ_1 , and Δ_2 are determined from the equations (9) on the basis of the equations (8) (for the Fourier zeugmatography) or the equations (24) (for the spin warp imaging), and then the value of g is calculated
15 from the equation (10). Next, the value of W is calculated from the equation (32), to determine the corrected image data $C(I, J)$ as follows:

$$C(I, J) = gW \dots\dots (33)$$

1 Thus, even in the case where the intensity
distribution of the static magnetic field is extremely
non-uniform so that the formulae (5) do not hold, the
distortion of the image caused by the non-uniformity of
5 the static magnetic field can be corrected.

Now, a method of measuring the intensity
distribution of a magnetic field in a field of view will
be additionally explained. The present invention deals
with the non-linearity of a static magnetic field and
10 the non-linearity of a gradient magnetic field which cor-
respond to about 0.001 percent of the intensity of the
static magnetic field. Such high-accuracy measurement c
cannot be made by a conventional magnetic field measuring
instrument (since the measuring accuracy of, for example,
15 a gaussmeter is about 0.1 percent of the intensity of a
static magnetic field), but can be carried out by a method
which utilizes the NMR phenomenon in the following manner.
That is, the frequency of the resonance signal is measured
at various positions in a field of view by moving a probe
20 which is formed by winding a signal detecting coil round
a tube having a diameter of about 1 mm and filled with
a substance to be imaged (for example, water). The
frequency f of the resonance signal is proportional to
the intensity H of the magnetic field, and the proportional
25 constant is equal to a gyromagnetic ratio. Accordingly,
the value of the magnetic field intensity H at a position
can be determined very accurately from the frequency f
of the resonance signal obtained at this position.

CLAIMS:

1. An imaging apparatus using the nuclear magnetic resonance and provided with means (1, 10) for forming a static magnetic field in a predetermined field of view, means (4x, 4z, 5, 6, 7, 8) for forming a gradient magnetic field in said field of view, means (3, 12, 13) for forming a high-frequency magnetic field in said field of view, signal detecting means (3, 14, 15) for detecting a nuclear magnetic resonance signal from a to-be-inspected body (2) placed in said field of view, and a computer (9) for performing an arithmetic operation for the detected signal to obtain the nuclear magnetic resonance signal intensity distribution in said field of view from measured values of said nuclear magnetic resonance signal intensity distribution at various points on a rectangular coordinate system in the Fourier space, said imaging apparatus comprising:

a first memory (17) for storing therein first image data, said first image data being obtained, by calculation, from the output of said signal detecting means, said first image data indicating said nuclear magnetic resonance signal intensity distribution in said to-be-inspected body on the basis of a measuring coordinate system; and

a second memory (18) for storing therein data with respect to the magnetic field intensity distribution in said field of view, to correct the coordinate of said first image data stored in said first memory on the basis

of said data stored in said second memory, thereby producing second image data, said second image data being displayed on a display device (16).

2. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second memory stores therein data indicating the spatial distribution of the deviation of the intensity of said static magnetic field from a predetermined value.

3. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second memory stores therein data indicating the spatial distribution of the deviation of the intensity of said static magnetic field from a predetermined value and data indicating the spatial distribution of the deviation of the intensity of said gradient magnetic field from a predetermined, linearly-varying intensity.

4. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second memory stores therein data previously calculated from measured values with respect to the intensity distribution of said static magnetic field and/or the intensity distribution of said gradient magnetic field for converting said first image data $C'(I', J')$ into said second image data $C(I, J)$ through the transformation of coordinate system.

5. An imaging apparatus using the nuclear magnetic resonance according to Claim 4, wherein coordinates ξ and η of said first image data corresponding to coordinates I and J on a to-be-displayed image (where $I = 0, 1, \dots, N-1$;

$J = 0, 1, \dots, N-1$) are divided into discrete coordinate components $\underline{i}$ and $\underline{j}$ and error components Δ_1 and Δ_2 as indicated by equations $\Delta_1 = \xi - i$ and $\Delta_2 = \eta - j$, and said second memory stores therein said discrete coordinate components $\underline{i}$ and $\underline{j}$ and said error components Δ_1 and Δ_2 .

6. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein said coordinates ξ and η are corrected by said components $\underline{i}$, $\underline{j}$, Δ_1 , and Δ_2 in such a manner that said second image data is obtained by interpolation from said first image data at four positions having coordinates $\underline{i}$ and $\underline{j}$, coordinates $\underline{i}$ and $\underline{j} + 1$, coordinates $\underline{i} + 1$ and $\underline{j}$, and coordinates $\underline{i} + 1$ and $\underline{j} + 1$.

7. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein said coordinates ξ and η are calculated substantially from the following equations:

$$\xi = I + \frac{1}{G_x} E(I, J)$$

$$\eta = J + \frac{1}{G_y} E(I, J)$$

where G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, G_y an intensity increment of a gradient magnetic field having an intensity gradient in a y-direction per one picture element, and $E(I, J)$ the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J .

8. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein said coordinates ξ and η are calculated substantially from the following equations:

$$\xi = I + \frac{1}{G_x} \{E(I, J) + h_1(I, J)\}$$

$$\eta = J + \frac{1}{G_y} \{E(I, J) + h_2(I, J)\}$$

where G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, G_y an intensity increment of a gradient magnetic field having an intensity gradient in a y-direction per one picture element, $E(I, J)$ the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J , $h_1(I, J)$ the deviation of the intensity of said gradient magnetic field having an intensity gradient in the x-direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J , and $h_2(I, J)$ the deviation of the intensity of said gradient magnetic field having an intensity gradient in the y-direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J .

9. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein a 180° high-frequency pulse is applied to said to-be-inspected body to detect said nuclear magnetic resonance signal, and said coordinates ξ and η are calculated from the following equations:

$$\xi = I + \frac{1}{G_x} \{E(I, J) + h_1(I, J)\}$$

$$\eta = J + h_2(I, J)$$

where x is taken in the direction of the gradient of a gradient magnetic field applied for measuring a nuclear magnetic resonance signal, G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x -direction per one picture element, $E(I, J)$ the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J , $h_1(I, J)$ the deviation of the intensity of said gradient magnetic field having an intensity gradient in the x -direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J , and $h_2(I, J)$ the deviation of the intensity of a gradient magnetic field having an intensity gradient in a y -direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J .

10. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second image data is an image signal whose intensity has been corrected by data stored in said first memory.

11. An imaging apparatus using the nuclear magnetic resonance according to Claim 4, wherein a 180° high-frequency pulse is applied to said to-be-inspected body to detect said nuclear magnetic resonance signal, and wherein one coordinate ξ of coordinates ξ and η of said first image

data corresponding to coordinates I and J on a to-be-displayed image is divided into a discrete coordinate component $\underline{i}$ and an error component Δ_1 as indicated by an equation $\Delta_1 = \xi - i$, and said second memory stores therein said coordinate component $\underline{i}$ and said error component Δ_1 .

12. An imaging apparatus using the nuclear magnetic resonance according to Claim 11, wherein said coordinate ξ is corrected by said components $\underline{i}$ and Δ_1 in such a manner that said second image data is obtained by interpolation from said first image data at two positions having coordinates $\underline{i}$ and J and coordinates $i + 1$ and J.

13. An imaging apparatus using the nuclear magnetic resonance according to Claim 11, wherein said coordinate is calculated from the following equation:

$$\xi = I + \frac{1}{G_x} E(I, J)$$

wherein G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, and $E(I, J)$ the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J.

14. An imaging method comprising the steps of:
 (a) measuring values of a nuclear magnetic resonance signal intensity distribution in a field of view at various points on a rectangular coordinate system in the Fourier

space,

(b) correcting values of coordinates in said measured values in a form of an image data with a data of a magnetic distribution measured in said field of view, and

(c) displaying said corrected values in said form of said image data in a display (16).

FIG. 1

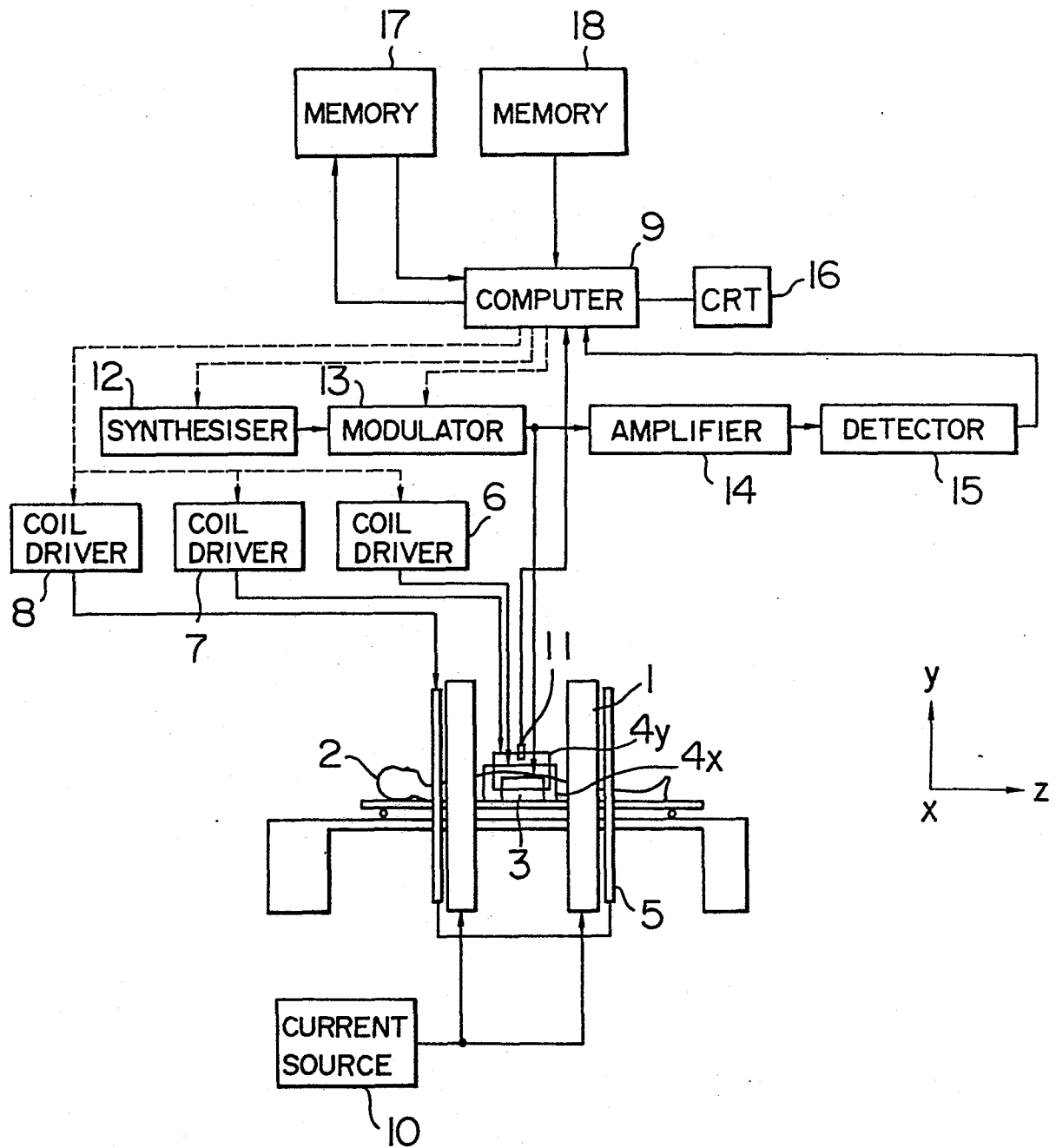


FIG. 2

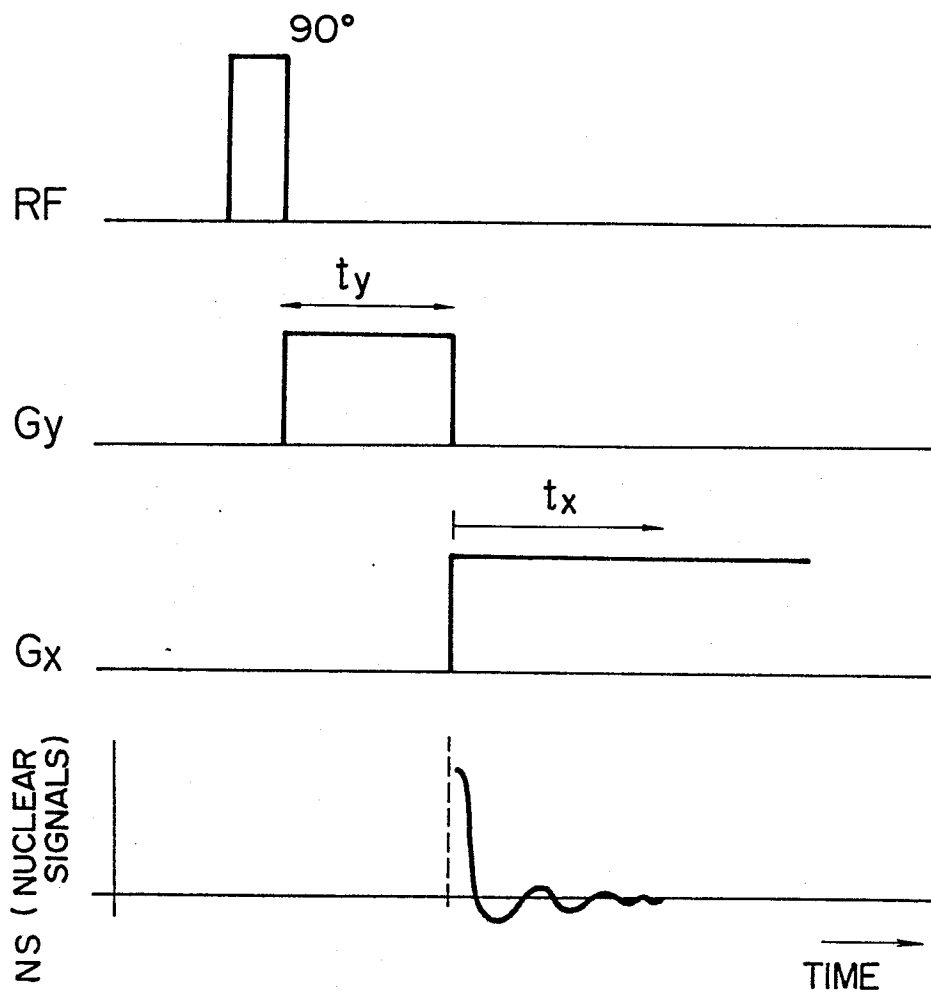


FIG. 3

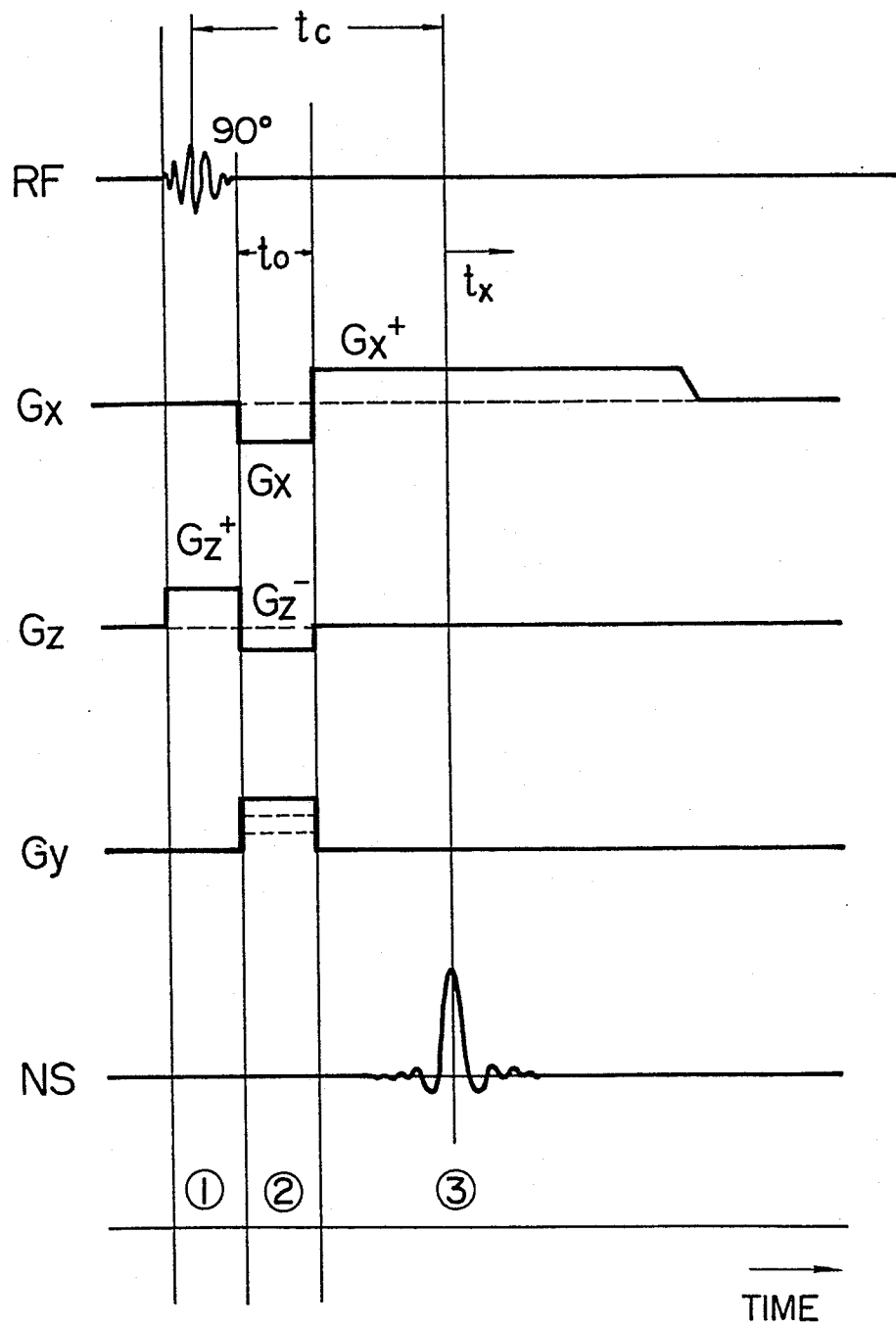


FIG. 4

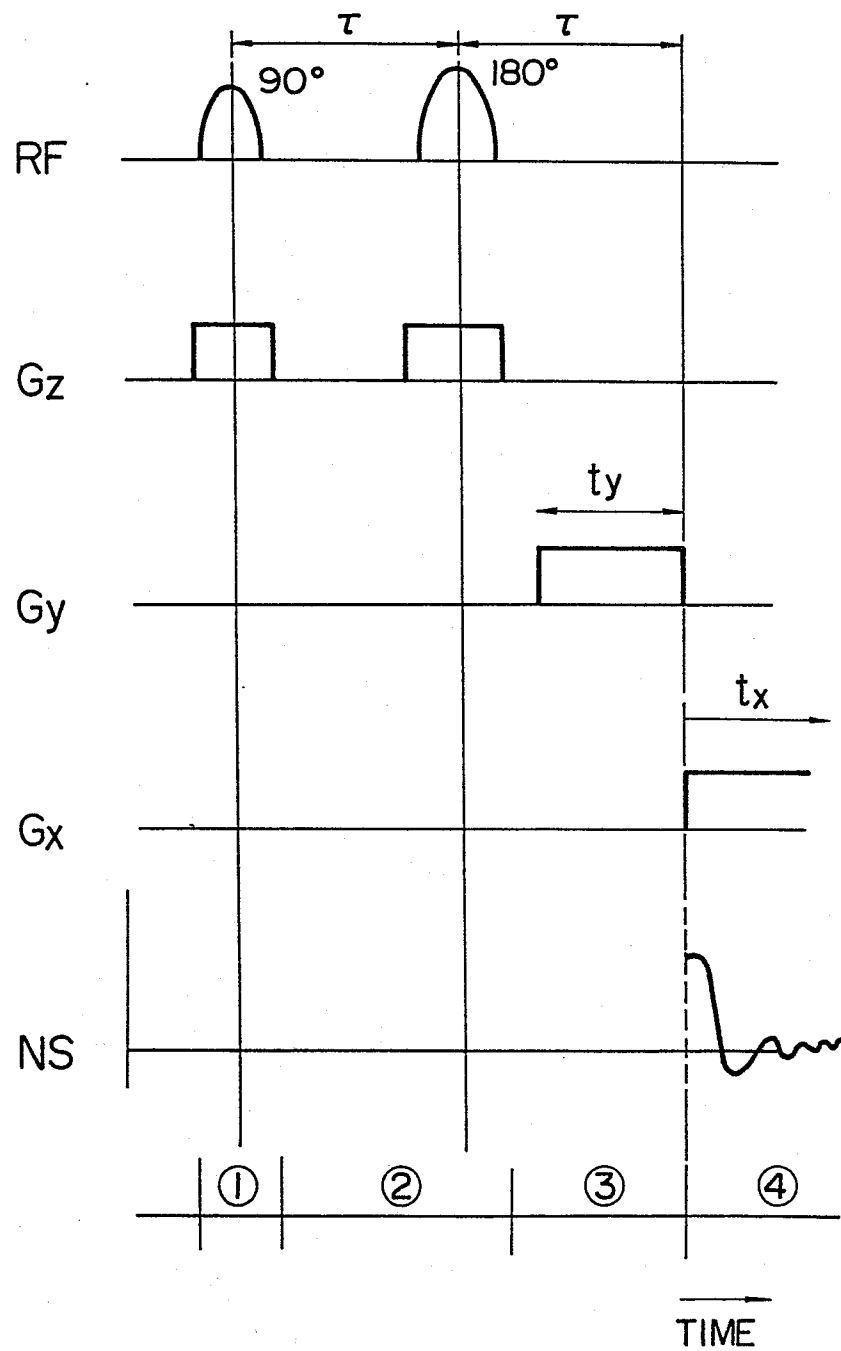


FIG. 5

